The Origin of the Correlation between the Spin Parameter and the Baryon Fraction of Galactic Disks

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Abstract. The puzzling correlation between the spin parameter λ of galactic disks and the disk-to-halo mass fraction f_{disk} is investigated. We show that such a correlation arises naturally from uncertainties in determining the virial masses of dark matter halos. This result leads to the conclusion that the halo properties derived from fits to observed rotation curves are still very uncertain which might explain part of the disagreements between cosmological models and observations. We analyse λ and f_{disk} as function of the adopted halo virial mass. Reasonable halo concentrations require $f_{disk} \approx 0.01 - 0.07$ which is significantly smaller than the universal baryon fraction. Most of the available gas either never settled into the galactic disks or was ejected subsequently. In both cases it is not very surprising that the specific angular momentum distribution of galactic disks does not agree with the cosmological predictions which neglect these effects.

1 Introduction

Within the framework of hierarchical cosmological structure formation galactic disks form from gas that falls into dark matter halos, where it cools and settles into the equatorial plane. The disk scale lengths and their rotation curves are determined by the gravitational potential and by their specific angular momentum distribution which has been acquired from cosmological torques (Hoyle 1953; Peebles 1969) and the random merging of subunits (Maller, Dekel & Somerville 2001) with additional modification during the dissipative protogalactic collapse phase. Cosmological simulations (Van den Bosch et al. 2002) have shown that the initial angular momentum distribution of the baryonic and dark matter component is similar. This initial condition could explain the observed scale lengths and various other properties of galactic disks, provided that the disk material retained its initial specific angular momentum when settling into the galactic plane (e.g. Fall & Efstathiou 1980; Mo, Mao & White 1998; Firmani & Avila-Reese 2000; van den Bosch 2001; Buchalter, Jimenez & Kamionkowski 2001).

In the past couple of years, high-resolution cosmological NBody/SPH simulations have however uncovered problems with this scenario. Baryons tend to lose a large fraction of their angular momentum to the dark matter while settling into a disk component. As a result, simulated galactic disks are an order

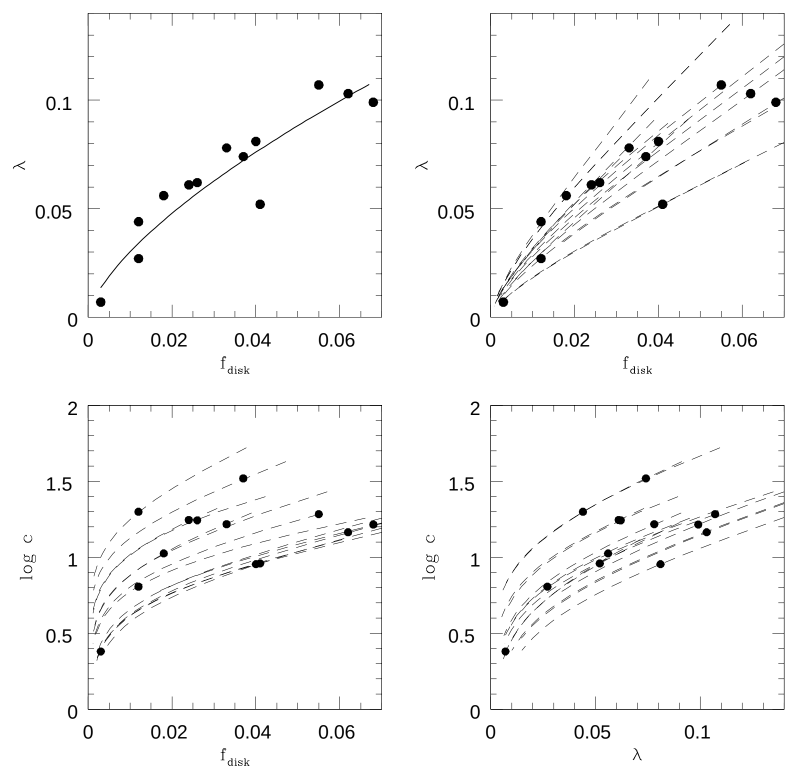

Fig. 1. Correlations between the disk spin parameter, the disk mass fraction and the halo concentration for the Swaters galaxy sample. Data points in the upper left panel show the best fit values with no constraints on the virial parameters, adopting a stellar mass-to-light ratio $\Upsilon_R = 1.0(M/L)_\odot$. The solid line in the upper left panel shows the correlation that would result from errors in determining the virial radii of dark matter halos. The dashed curves in the other panels show for each galaxy how the data points shift if one determines the best fitting rotation curve for different values of the virial radius.

of magnitude smaller than observed (Navarro & Benz 1991; Navarro & Steinmetz 1997). Even if the angular momentum would be conserved, the observed disk angular momentum distribution does not agree with theoretical predictions. This was shown by van den Bosch, Burkert & Swaters (2001), who measured in detail the angular momentum distribution for a sample of dwarf disk galaxies by fitting a NFW profile (Navarro, Frenk & White 1997) to the observed rotation curves, taking into account the disk stars and the HI gas and considering adiabatic contraction and beam smearing. They confirmed that the mean specific angular momentum of the disk material is of the same order as expected if angu-

lar momentum is conserved during the protogalactic collapse phase. Their case by case studies however revealed a mismatch of the specific angular momentum profiles of galactic disks, compared with the predicted universal dark halo angular momentum distribution of Bullock et al. (2001): the cosmologically predicted mass fraction with low angular momentum is much larger than observed.

The problem of angular momentum loss during gas infall might partly be solved by energetic feedback processes. Thacker & Couchman (2001), for example, showed that stellar heating could decouple the dynamical evolution of the protogalactic gas with respect to the dark halo, leading to galactic disks with a specific angular momentum that is within 10% of the observed value (see also Sommer-Larsen et al. 1999, Navarro & Steinmetz 2000, Maller & Dekel 2002). Still, as demonstrated by van den Bosch et al. (2002), a large fraction of the baryonic component would have very low or even negative specific angular momentum, in contrast with the observed disk angular momentum distribution. It has also been suggested that this low-angular momentum gas could form large galactic bulges instead of disks (Thacker & Couchman 2002, van den Bosch et al. 2002). These bulges are however not observed in the LSB galaxies, studied by Van den Bosch, Burkert & Swaters (2001).

In addition, van den Bosch, Burkert & Swaters (2001) detected a strong correlation between the disk spin parameter and the disk mass fraction for the Swaters sample. A similar correlation for a much larger sample of LSB and HSB galaxies has been found by Jimenez, Verde & Oh (2002). This result is puzzling. It is not clear why the fraction of baryonic material that forms the observed galactic disks should correlate with the disk spin parameter.

2 The origin of the correlation between spin and disk mass fraction

The upper left panel of figure 1 shows the observed correlation between the disk spin parameter

$$\lambda = \gamma \frac{j_{tot}}{\sqrt{2} R_{vir} V_{vir}} \tag{1}$$

and the disk mass fraction $f_{disk} = \frac{M_{disk}}{M_{vir}}$, with M_{disk} the total disk mass and $M_{vir} = V_{vir}^2 R_{vir}/G$ the virial mass of the dark halo. Here γ is a geometrical factor which depends on the dark matter density distribution, j_{tot} is the observed total disk angular momentum and R_{vir} and V_{vir} are the virial radius and virial mass of the dark halo, respectively. These values represent the best fit to the rotation curves if no constraints are imposed on R_{vir} and V_{vir}. A dependence of disk rotation on the disk mass fraction might provide interesting new insight into the evolution of disk galaxies. However it also could emerge from uncertainties in determining the dark halo properties. All the information about the structure of the dark matter halos is gained through disk rotation curves which are restricted to the inner halo regions. The outer halo regions and especially their virial masses or virial radii are poorly constrained. In addition, tests show that the fits to the

observed rotation curves are almost equally good for a large range of virial values. Both, λ and f_{disk} depend on R_{vir}. As γ does not vary strongly with halo mass and with $V_{vir} \sim R_{vir}$ we find $\lambda \sim R_{vir}^{-2}$ and $f_{disk} \sim R_{vir}^{-3}$. Any error in R_{vir} will therefore shift the data points along a curve $\lambda \sim f_{disk}^{2/3}$ which is shown by the solid curve in the upper left panel of figure 1. The good agreement of the distribution of the data points with this relationship indicates indeed that the correlation results from errors in determining R_{vir}. This problem is shown in more details and for each galaxy separately in the right upper panel of figure 1, where the dashed curves show the best fit values of λ and f_{disk} for all galaxies, adopting different values of R_{vir}.

3 Conclusion

The correlation between λ and f_{disk} that has been found by van den Bosch et al. (2001) or Jimenez et al. (2002) can be explained as a result of uncertainties in determining the dark halo virial radii or masses. Cosmological models predict that most of the protogalactic gas with a cosmological baryon fraction (for LCDM) of $f_{bar} = \Omega_{bar}/\Omega_0 \approx 0.13$ loses 90% of its angular momentum and settles into the equatorial plane, leading to typical values of $\lambda \approx 0.005$ and $f_{disk} \approx 0.13$. Even if the virial radius is unknown and treated as a free parameter, the upper right panel of figure 1 clearly shows that these values can be ruled out.

Dark matter halos have typical concentrations of order $c \approx 12 - 15$ which should not be affected strongly by the dynamical evolution of the baryonic component in dark matter dominated LSB galaxies. The lower panels of figure 1 show that $f_{disk} \approx 0.01 - 0.07 < f_{bar}$ for these halo concentrations. The galaxies either lost a substantial fraction of their baryons in a galactic wind or accreted only a small fraction of the gas that has been available initially. In both cases, there exists no reason why the specific angular momentum distribution of the disk component should match the dark halo angular momentum distribution as assumed e.g. by Mo, Mao & White (1998). The cosmological angular momentum problem of disk galaxies might therefore be connected directly with the origin of their low baryon fractions.

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